



*Advanced Exploration Systems Program*

# ***Automated Transfer Vehicle Material Flammability Experiment***

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# ***Automated Transfer Vehicle Material Flammability Experiment***



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➤ *Members of the Spacecraft Fire Safety International Topical Team*

# Automated Transfer Vehicle Material Flammability Experiment



## Objective:

Advance spacecraft fire safety technologies through **a large-scale fire demonstration in low gravity.**

- A large-scale experiment aboard an unmanned re-entry vehicle would investigate important questions about low-gravity material flammability
- Demonstration of the operational concept could allow future experiments to investigate fire detection and suppression equipment and protocols.

## Relevance to Human Space Flight:

The material flammability questions to be addressed in this experiment were identified during the design of the ECLS system for Orion, Altair, and Lunar Surface Systems

- Addresses knowledge gaps that must be resolved for assured protection of a spacecraft from fire hazards

*Most U.S. agencies responsible for large transportation systems conduct full-scale fire tests to address gaps in fire safety knowledge and prove equipment and protocols.*



FAA full scale aircraft test

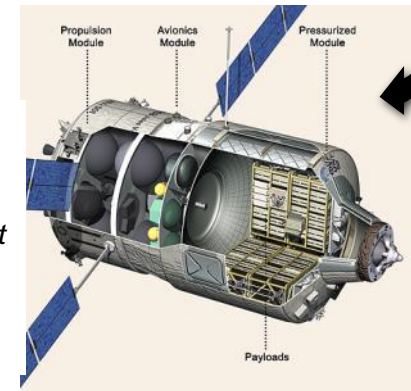


Naval Research Laboratory  
Ex-USS Shadwell



ESA ATV approaching the  
ISS

*Cut-away of the Automated Transport Vehicle (ATV). The large-scale experiment could be conducted in one of the standard payload racks.*

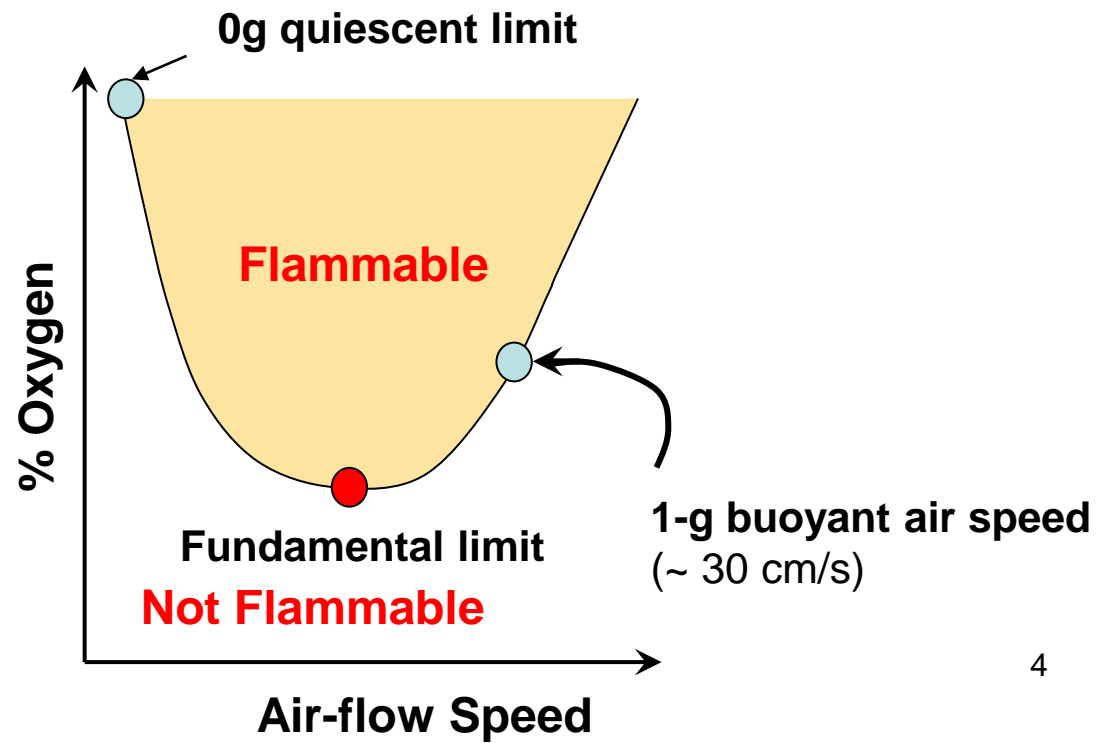


# Experiment Justification



- How different are low-g material flammability limits from those measured in normal gravity?
  - Low-gravity oxygen flammability limits are different in low-gravity than in normal gravity
  - Normal gravity flames induce a natural convective flow that transports oxygen to the flame but also removes heat
  - Forced convection in low-g transports oxygen to the flame but rate of heat removal is reduced
    - The normal-gravity (and partial-gravity, for that matter) oxygen concentration flammability limit is not necessarily the minimum

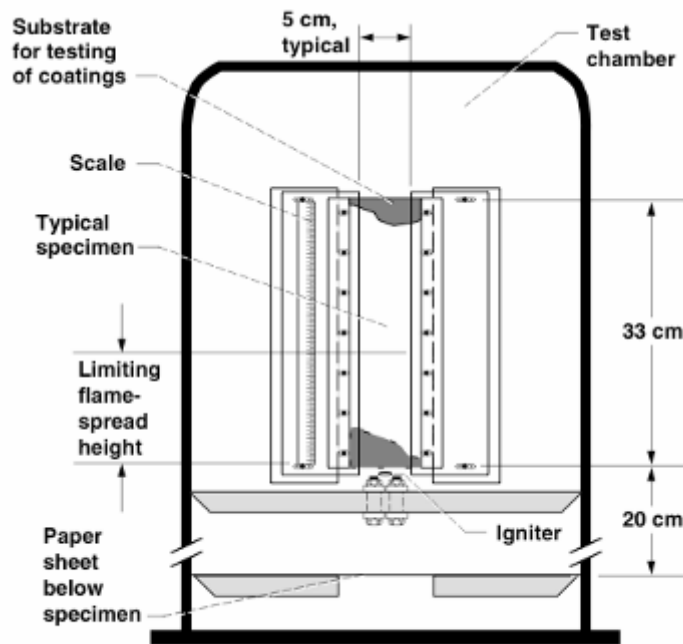
- What is the fate of a large-scale fire in low-gravity?
  - Extrapolation of observed low-g flame behavior to a full-scale spacecraft fire scenario is tenuous
  - Fires on-board spacecraft have been few – fortunately
  - Experience with “significant” fires is very limited
    - Enhance risk assessments and modeling of fire events



# Experiment Justification



- NASA-STD-6001 describes the test methods used to qualify materials for use in space vehicles.
- The tests cover flammability, odor, off-gassing, and compatibility.
- The primary test to assess material flammability is Test 1: Upward Flame Propagation



**Test 1 Apparatus**

CD-99-78888

- Materials “pass” this test if the flame self-extinguishes before it propagates 15 cm
  - Maximum oxygen concentration (MOC) is defined as the highest  $O_2$  at which material passes Test 1
  - Flammability limits determined by this test are strongly influenced by natural convection
  - Samples are 5 cm wide x 33 cm long and rigidly held in a frame
- *Flammability samples*

# Low-g Oxygen Flammability Threshold Tests

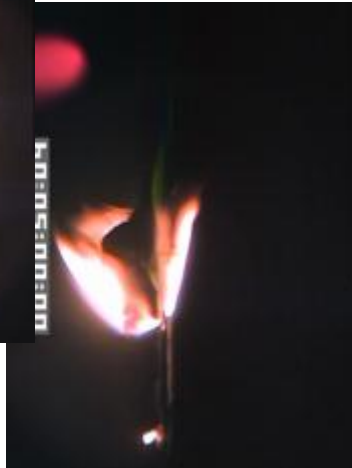


- Tests conducted in the Zero Gravity Facility at NASA-GRC to quantify the low-g flammability thresholds for typical spacecraft materials

*Ultem 1000*



*Nomex*



*Mylar*



*ZGF drop tower rig with  
Combustion Tunnel  
facility*



- 5.2-sec limits samples to thin materials

# Lunar-g Maximum Oxygen Concentration



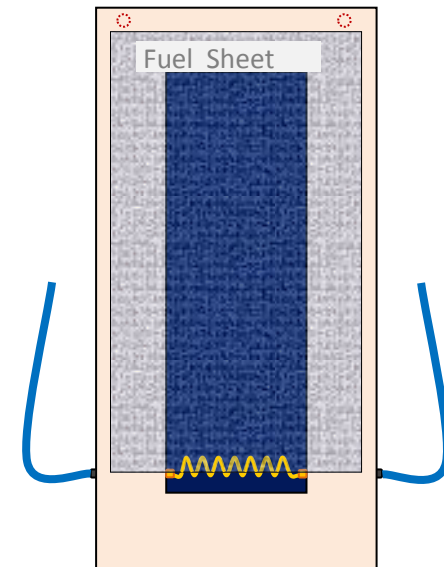
- Centrifuge drop rig being prepared for a drop in the Zero Gravity Facility.
- Fuel sample is 5 cm wide by 6 cm long.



*Dome*

*Experiment  
support plate*

*Control  
hardware and  
electronics*

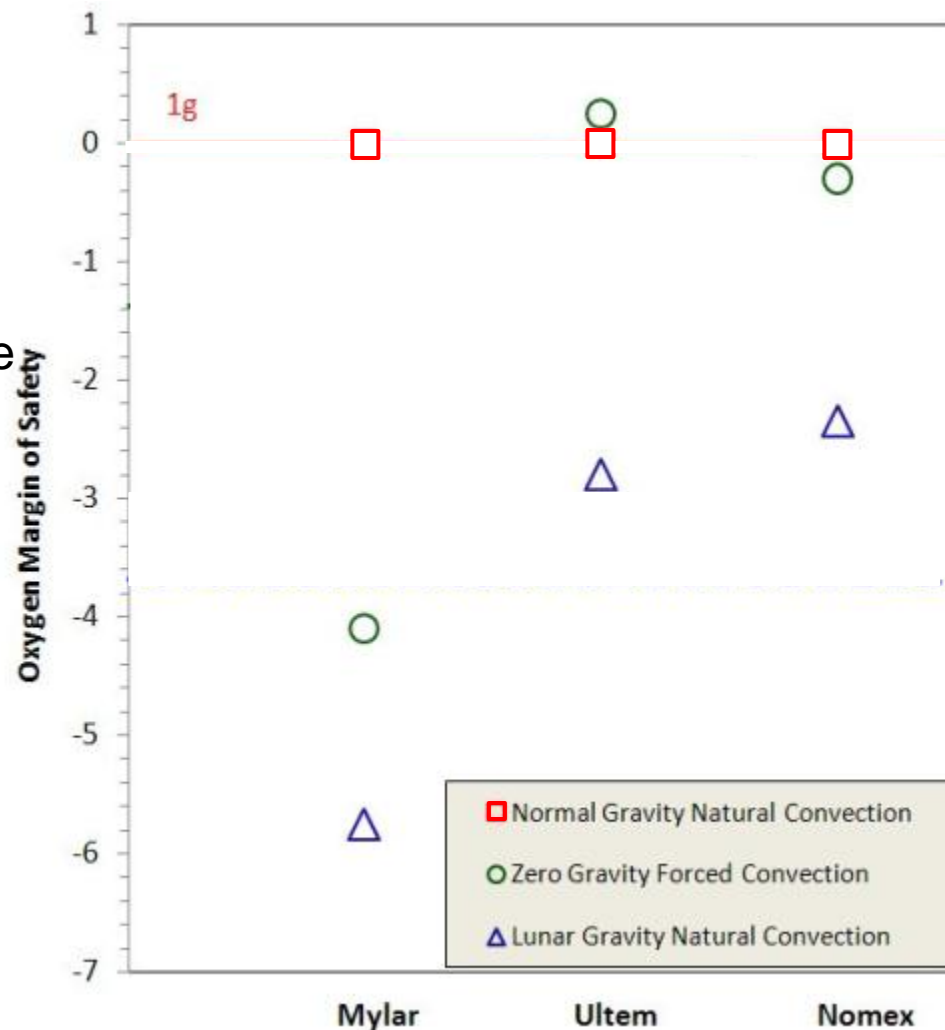


# Zero-g and Lunar-g MOC Results



- Tests were conducted at WSTF (normal-g) and GRC (Lunar-g) to quantify changes in the MOC for Nomex, Mylar, and Ultem
- Conditions run in Lunar-g burned at both the normal gravity MOC and at the zero-g convective MOC
  - Lunar-g flammability appears more like zero-g rather than 1-g
  - Cessation of ventilation flow is not effective
- Significant impact on a fire safety strategy, especially if the need for fire detection and suppression is dictated by the difference between the MOC and atmosphere of use.

(MOC: Highest O<sub>2</sub> concentration where sample passes Test 1)

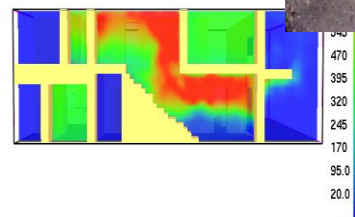


# How rapidly can a fire spread in low-g?



- This question lies at the heart of the development of a fire safety strategy
  - Terrestrial or spacecraft applications
- Rate of fire growth impacts:
  - Time to detect
    - Early detection reduces impact of fire, response strategy
  - Size of fire
    - Amount of fire suppression agent required
  - Heat release rate, fire spread to surrounding materials
    - Collateral damage
  - Emission of combustion products
    - Post-fire cleanup strategy and consumables
- Large-scale *flame spread* sample
  - 0.5 m wide x 1.0 m long

*NIST Full Scale Fire test*



Time: 605.0



*FAA full scale aircraft test*



*Side view of a low-g flame on a thin paper sample in a concurrent convective flow*

# Science Objectives – Fire Safety - 1

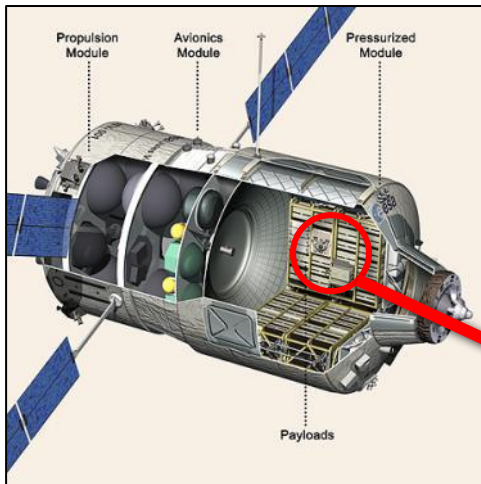


- Science objectives developed by the Spacecraft Fire Safety International Topical team
  1. Examine the applicability of upward flammability tests such as NASA STD 6001, Test 1
  2. Observe and quantify the growth and spread of a large-scale fire
  3. Develop an active system based on fire modelling that provides optimised mitigation strategies based on the characteristics of a fire as it occurs.
  4. Quantify the soot concentration field during the growth and spread of a large-scale low-g fire
  5. Determine the impact of fuel surface structure on spread rate and flammability limits of flames
  6. Extend the impact of ground-based testing by comparing flight data with that from Japanese small scale flight experiments.
  7. Quantify the impact of a metallic skeleton of high thermal conductivity in a material on flame spread
  8. Demonstrate the filtering capability of advanced post-fire clean-up system.
  9. Quantify the combustion products of experiment sample materials using a suitable array of gaseous monitors

# Experiment Concept



## Avionics Bay



## Test Samples

Different Geometries  
(e.g. parallel and  
corners) and materials

## Fan & Filter Modules

## Experiment Configuration and Sequencing:

- Two sets of sample configurations

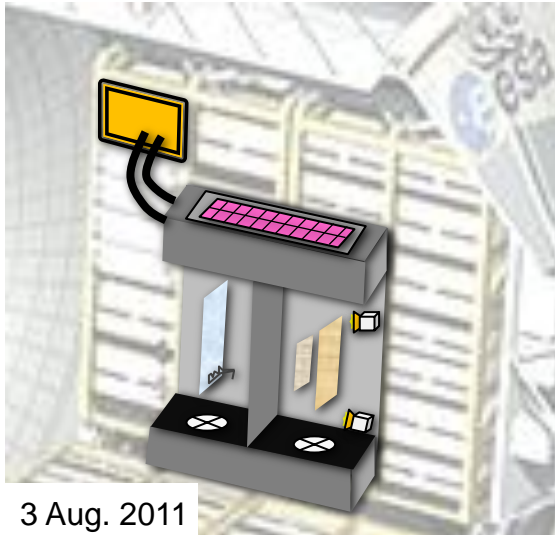
Flammability Limits: Series of 5 x 30 cm samples selected to test the flammability limit

Flame Spread: Large sample to study fire growth

## Concept of Operations:

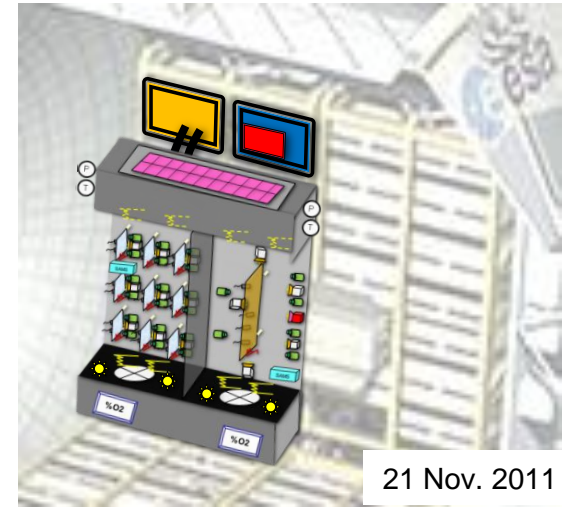
- Experiment would be launched in soft stowage bags
- Experiment would be assembled by the crew while loading the ATV for undocking
- Tests would be executed sequentially.
- Data to be transmitted to ground.

# Experiment Description



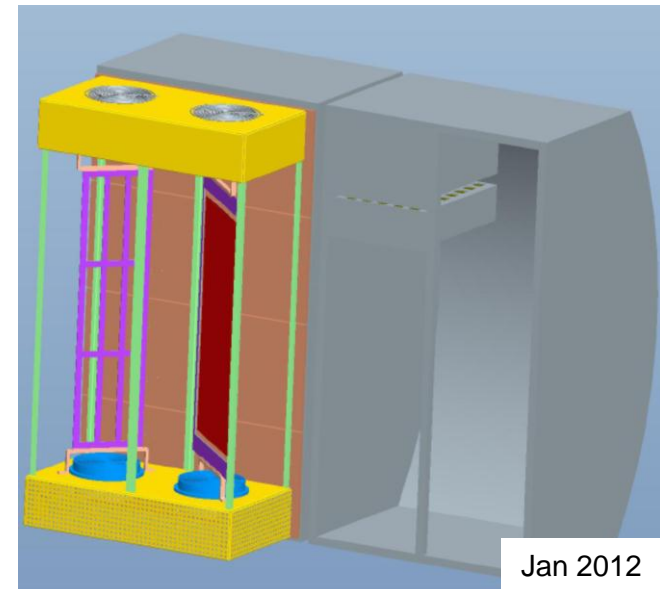
## Diagnostic Equipment:

- Lights
- Cameras
  - Movie
  - Stills
- Pressure Sensor
- Temperature Sensor
- Oxygen Concentration
- Fire Detection Sensors

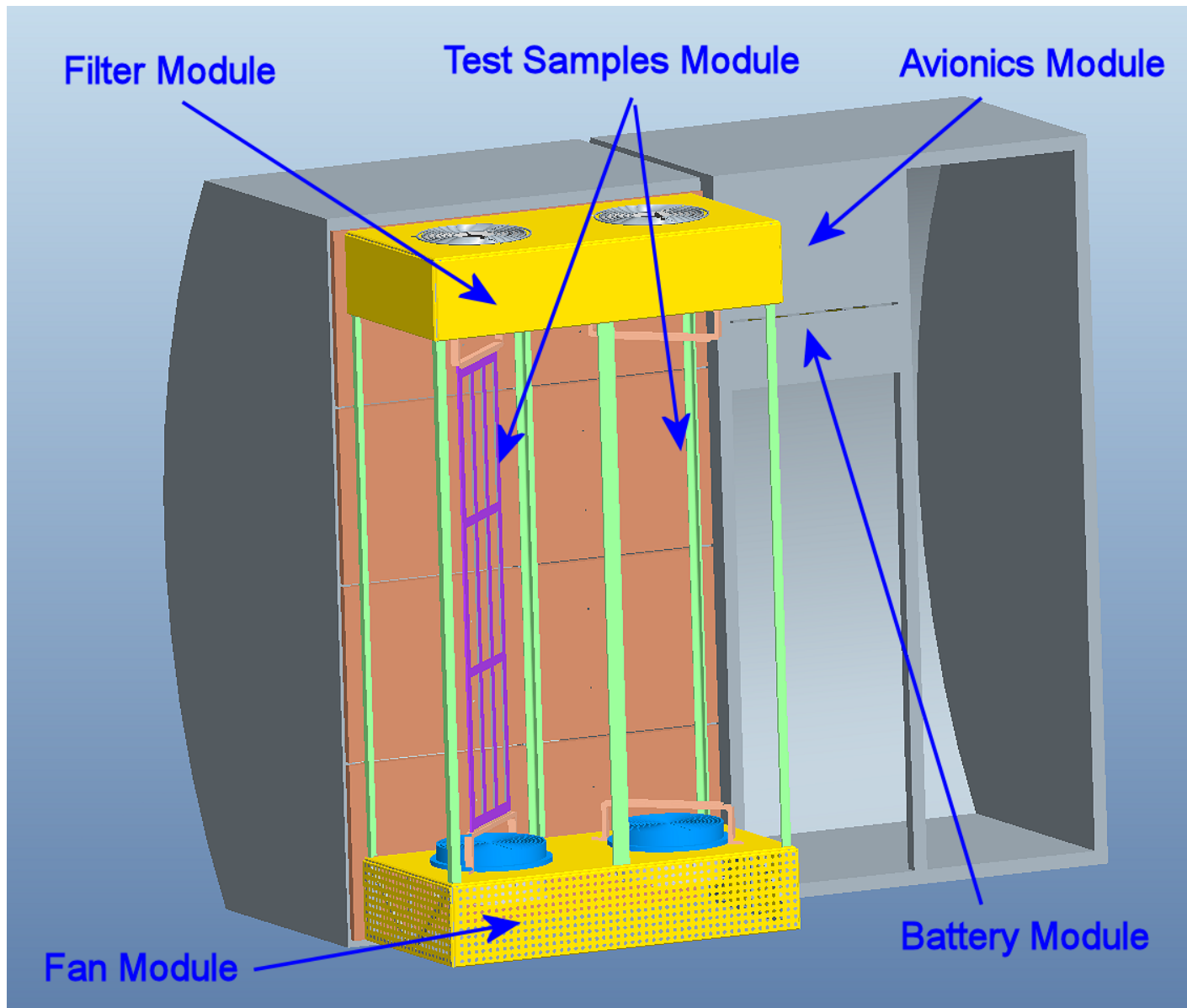


## Experiment Equipment:

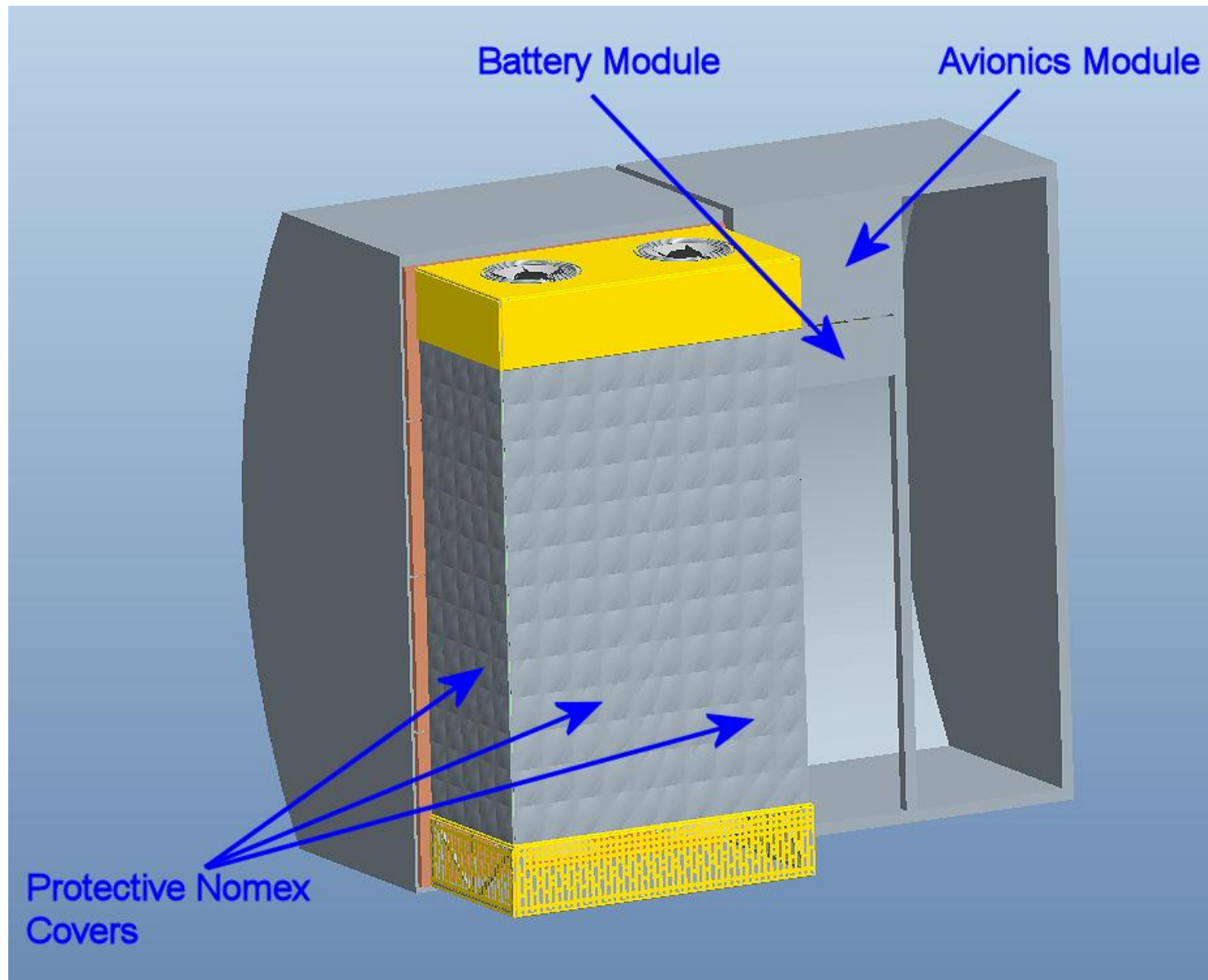
- Fans
- Support Plate
- Smoke Cleaning Material
- Protection Screen
- Ignition System
- Test Material
- Extinguishing Agent
- Command, Control, and Data Computer
- Communication Link (antenna, wiring, interfaces)



# CAD Model of Experiment installed in ATV Rack



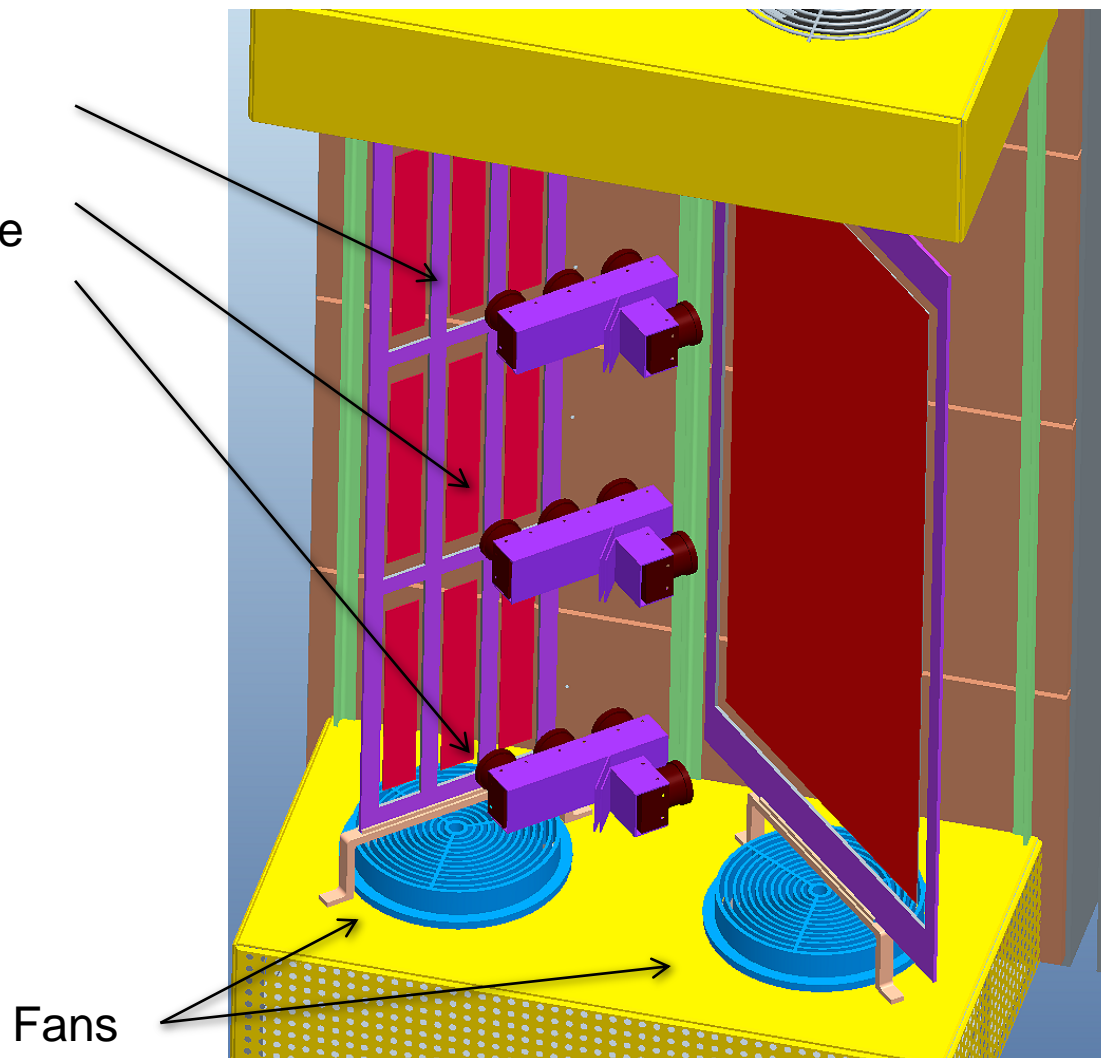
# CAD Model of Experiment - *Protective Nomex Covers*



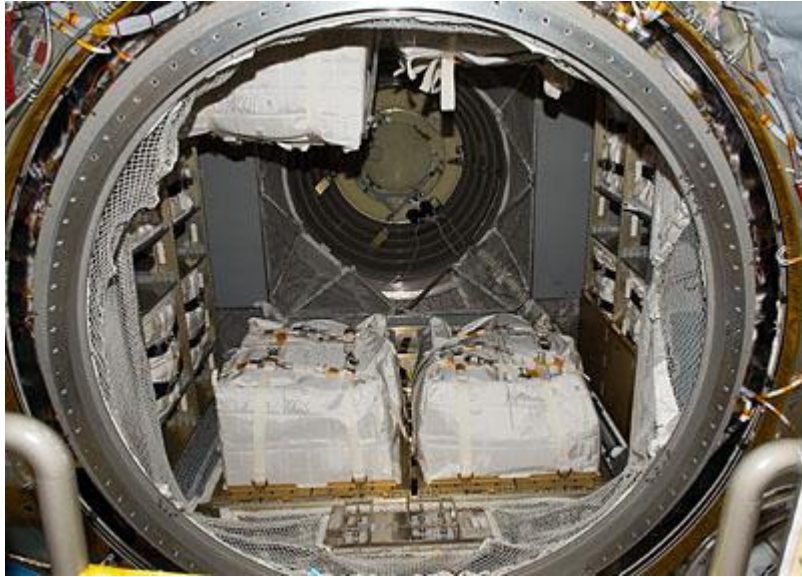
# CAD Model of Experiment - *Diagnostics*



- Camera array assembly
  - one on each flammability sample
  - three camera array on flame spread sample
- Lights contained in each assembly
- Anemometers
- Gas sensors ( $O_2$ ,  $CO_2$ ,  $CO$ )
- Pressure, temperature



# Mission Concept



*Load onto an ATV in a cargo bag*



*ATV in shroud on an Ariane V*



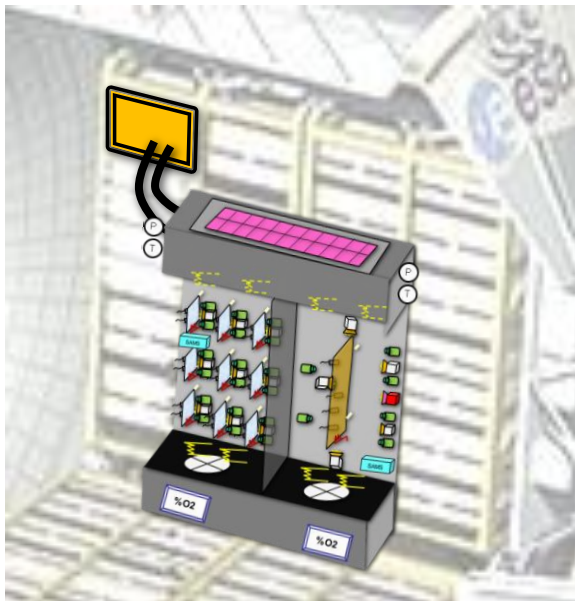
*Ariane V launch*

# Mission Concept



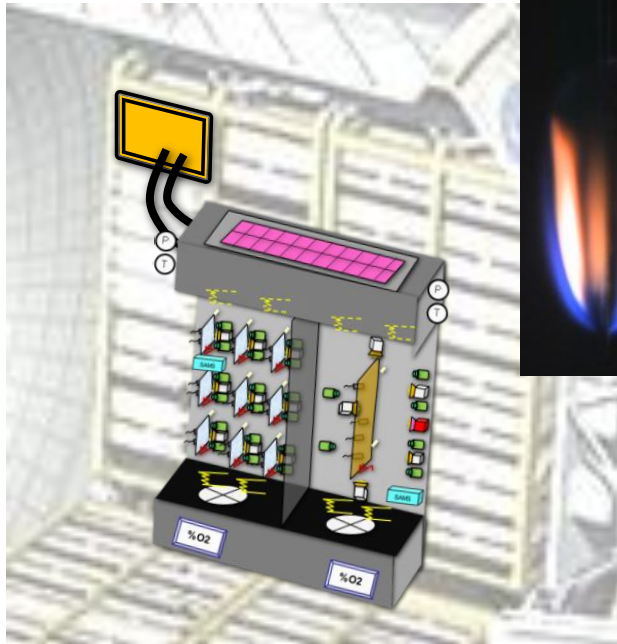
*Dock to ISS*

*Unpack cargo, reload with trash*



*Unstow SFS Demo experiment and mount to plates on front of racks*

# Mission Concept

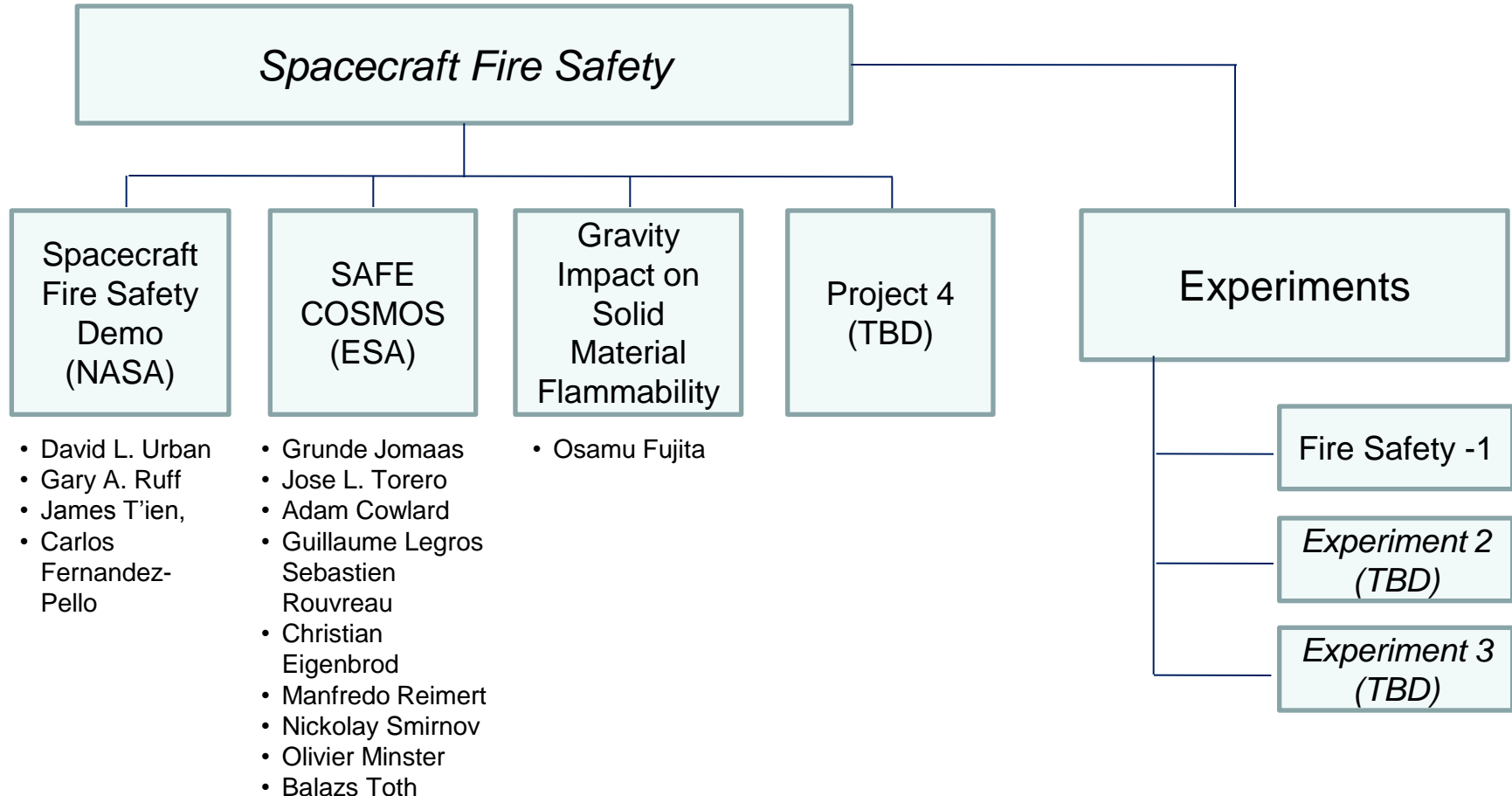


*Side view of a low-g  
flame on a thin paper  
sample in a convective  
flow*



*ATV-1 re-entering the atmosphere*

# Spacecraft Fire Safety Topical Team

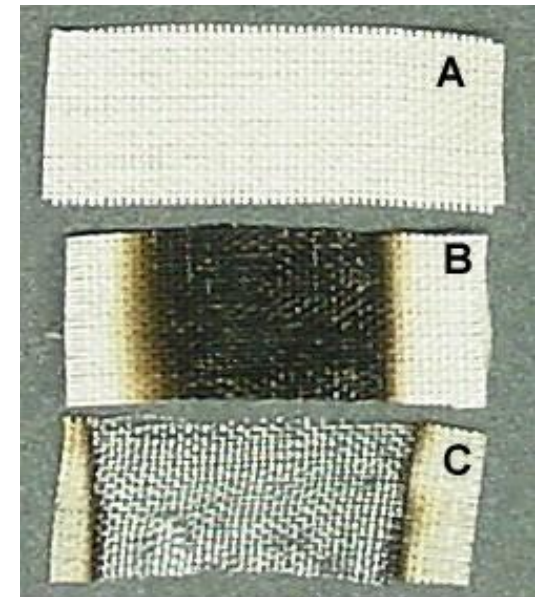


- Primary activities of the international topical team include:
  - Development of the experiment requirements
  - Sample selection and configuration
  - Vehicle pressure control
  - Command, control, and data down-linking
- The European Space Agency kicked off a feasibility study in October 2011
  - Report completed in late December 2011
- Initial draft of the ESA Experiment Science Requirements (ESR) document was completed in early November
  - ESR will continue to be updated as experiment requirements develop

# Sample selection – Fire Safety - 1



- Constraints on sample material include (1) material flammability limits (1-g and 0-g), (2) flame propagation rate, (3) material stability, (4) smoke production, (5) heat release, (6) ease of ignition, (7) mounting, ...
  - Material flammability samples: up to 9 samples (5 cm x 30 cm)
  - Flame spread sample (50 cm x 100 cm)
- Sample characteristics
  - cellulose (paper or cotton fabric)
  - Possible additional of an inert support material (fiber glass)
- Density of fuel: no greater than 9 mg/cm<sup>2</sup> of fuel
  - The inert material would affect the density but will not affect the heat release
- Science team members are investigating other sample configurations
  - corrugated surfaces
  - ridges
  - Corners
- Sample materials and objectives for future flights will be developed based on the results of Fire Safety - 1



**Figure 1:** Images of the cotton/fiberglass fuel. A) The virgin fuel. B) An images of the fuel after flame passage (some cotton remains). C) An image of the fiberglass matrix alone (the cotton is burned away).

# Pressure Control in ATV



- ATV maximum pressure is 1048 hPa (mBar)
  - ATV engineering limit is 1035 hPa
  - Assumed initial pressure is 1023 hPa
- Internal pressure can be decreased but ATV engineers estimated that a desired pressure could be achieved only to within +/- 100 hPa
- We have developed a transient lumped-parameter model that accounts for heat release from the sample and heat transfer to the vehicle and contents

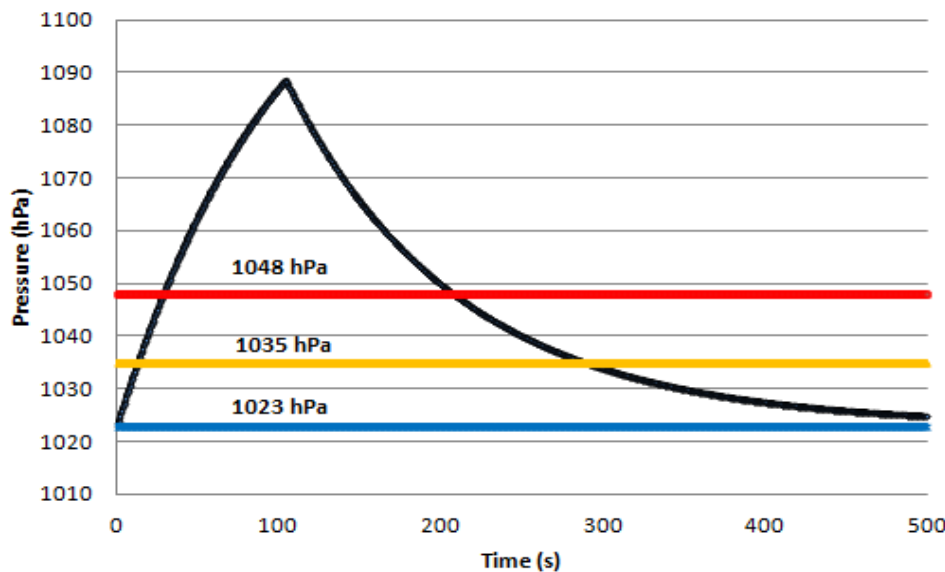
Condition	Large Sample		Small Sample		Number of Small Samples	Fuel mass (g)	T <sub>o</sub> (K)	P <sub>o</sub> (hPa)	Conductive loss area (cm x cm)	T <sub>max</sub> (K)	P <sub>max</sub> (hPa)	Average Rate of Pressure Rise (hPa/s)
	width (cm)	length (cm)	width (cm)	length (cm)								
1	50	100	10	30	9	69.3	294	1023	N/A	313	1089	0.63
2	50	100	10	30	9	69.3	294	1023	50 x 20	299	1039	0.15
3	50	100	10	30	9	69.3	294	950	N/A	314	1014	0.61
4	25	50	5	30	4	16.7	294	1023	N/A	300	1043	0.40

# Estimation of Pressure Rise



Condition	Large Sample		Small Sample		Number of Small Samples	Fuel mass (g)	$T_o$ (K)	$P_o$ (hPa)	Conductive loss area (cm x cm)	$T_{max}$ (K)	$P_{max}$ (hPa)	Average Rate of Pressure Rise (hPa/s)
	width (cm)	length (cm)	width (cm)	length (cm)								
1	50	100	10	30	9	69.3	294	1023	N/A	313	1089	0.63
2	50	100	10	30	9	69.3	294	1023	50 x 20	299	1039	0.15
3	50	100	10	30	9	69.3	294	950	N/A	314	1014	0.61
4	25	50	5	30	4	16.7	294	1023	N/A	300	1043	0.40

**Pressure Rise**

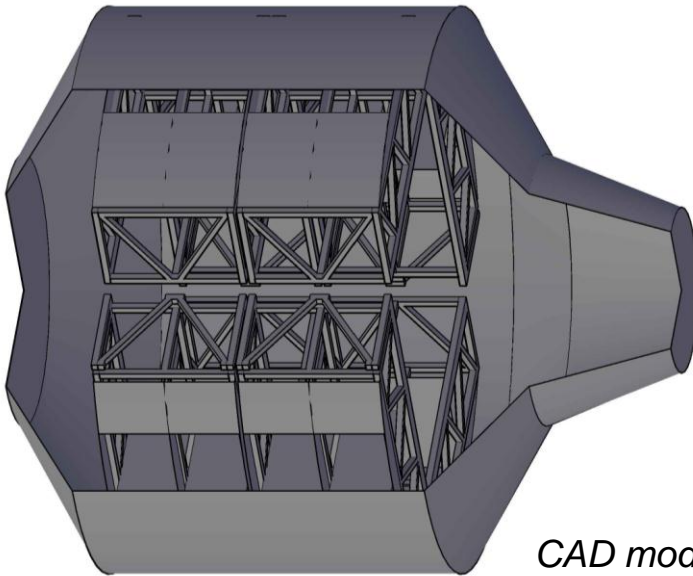


- Rate of pressure rise for Condition 1 – Transient, lumped-parameter model
- Assumes a constant burning rate based on low-g data
- Burning rate and heat release data will be required for any sample material

# Full-Scale Environment Effects



- Conduct tests in a vacuum chamber at GRC on full-scale demonstration using candidate materials and configurations
- Characterize the transient pressure and temperature environment
- Compare data with estimates and modeling results



*CAD model of ATV interior to be used in detailed modeling of the Fire Safety – 1 experiment. (Internal racks are not filled in this image.)*

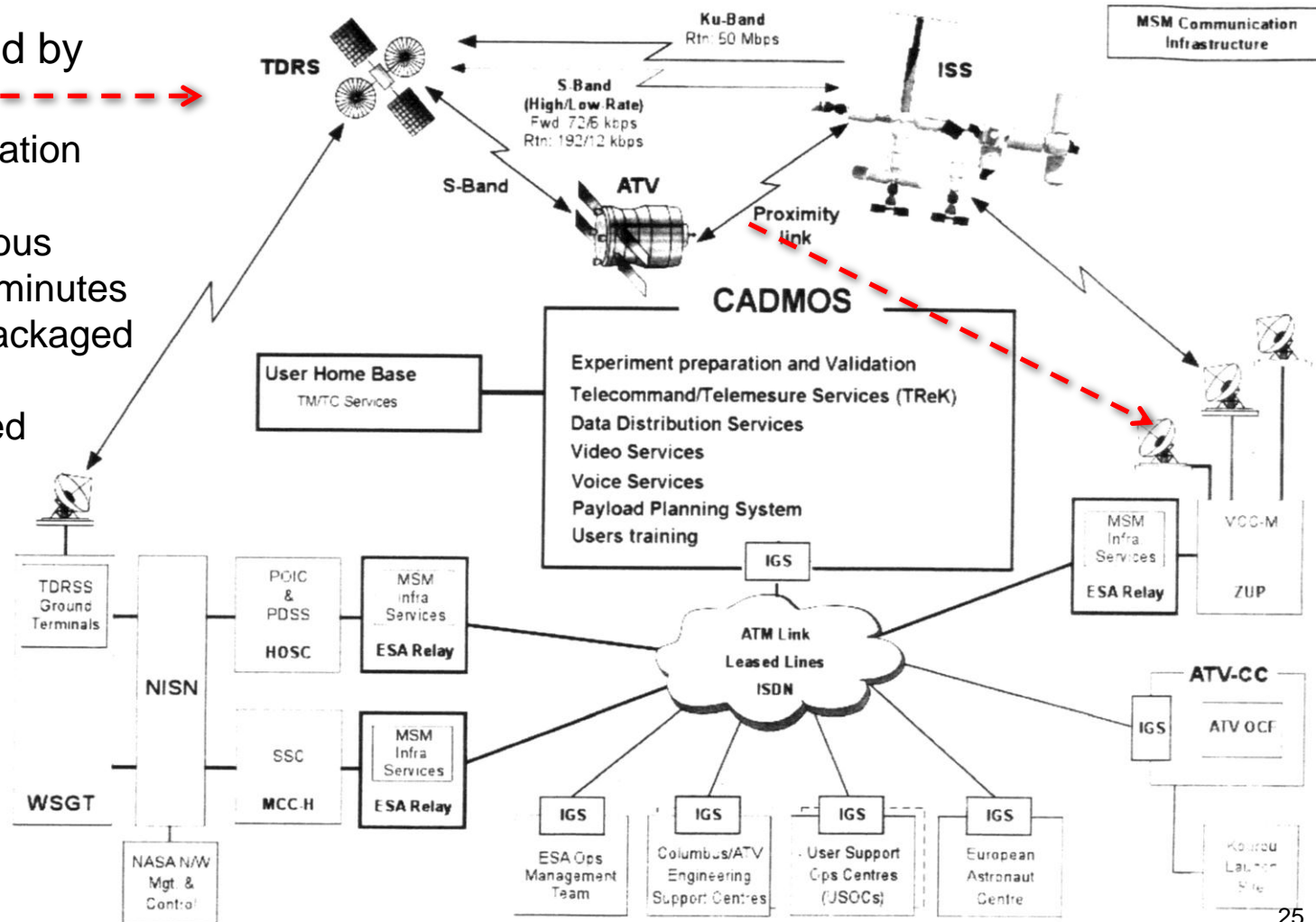


*VF-13 Pressure Vessel (5' diameter x 11' tall) that allows testing of full-scale samples*

# Command, Control, and Data Down-link



- Options range from minimal C&C to having the ability to review data between runs
- Experiment communications to remain isolated from vehicle command and control
- S-band suggested by ESA ----->
  - Antenna and location available
  - Longest contiguous downlink is ~22 minutes
  - Data could be packaged into files, each download initiated with a “start” command
- X-band options are being investigated by NASA
- Availability of a transponder is an issue



- A Spacecraft Fire Safety International Topical Team has been formed and is developing requirements for a unique large-scale fire safety experiment to be performed on the Automated Transfer Vehicle
  - Tests planned for ATV-5 (March 2014) pending the results of the ESA ATV Feasibility Study
  - NASA Project Team is developing and building the experiment
    - Advanced Exploration Systems Program, Spacecraft Fire Safety Demonstration Project
- Initial tests will focus on material flammability
  - Low-g flammability limits
  - Large-scale flame spread
- Current activities of the science team include evaluation of pressure rise and control options in the ATV, selection of sample materials, and development of alternative for communications
- Long lead time items include:
  - S- or X-band transmitter
  - International agreements